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Large-Scale Assignment of Congested Bicycle Traffic Using Speed Heterogeneous Agents

Mads Paulsen[a,*], Kai Nagel[b]

[a]Technical University of Denmark, Department of Management Engineering, Bygningstorvet 116B, 2800 Kgs. Lyngby, Denmark
[b]Technische Universität Berlin, Transport Systems Planning and Telematics, Salzufer 17-19, 10587 Berlin, Germany

Abstract

Despite requiring less space than most other modes of transport, bicycle traffic will also be prone to congestion when the traffic volume is sufficiently large. Such congestion can eventually influence the route choices of cyclists using the network. In this study we model bicycle congestion on a detailed network of the greater Copenhagen area by assigning an entire day of bicycle traffic using a recently developed method for dynamic network loading of speed heterogeneous multi-lane bicycle traffic. The model iteratively assigns appropriate routes for more than a million bicycle trips in the demand sensitive network, and with computation times of less than 15 minutes per iteration the proposed model proves to be large-scale applicable. This makes it the first dedicated bicycle traffic assignment model to account for congestion. The results indicate that the solid bicycle infrastructure of Copenhagen and cyclists' willingness to change routes are key to keeping travel times low for cyclists.

Keywords: Bicycle traffic assignment, bicycle congestion modelling, multi-agent simulation, speed heterogeneity

1. Introduction

Although congestion on bicycle tracks may seem unlikely many places in the world, in some cities (e.g. Copenhagen) the traffic level of bicycles has reached a level which leads to considerable bicycle congestion. The congestion influences the travel time, and may also influence cyclists' route choice.

For decades the literature[1] has been concerned with how the level-of-service for cyclists is influenced by the car traffic volume. However, including the flow of bicycles as a parameter of attractiveness of a route has only received little attention in the literature. Two stated preferences studies[2,3] found that cyclists generally have disutility towards increasing bicycle flow on bicycle lanes in Nanjing, China. This indicates that the more cyclists using a link, the less attractive the link will become. In traffic assignment for motorised traffic such disutility can be explained by

* Corresponding author. Tel.: +45 45 25 65 98.
E-mail address: madsp@dtu.dk

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increased travel time modelled with a flow-dependent travel time function for each link[4]. However, for bicycle traffic assignment only a single model[5] has so far incorporated a mechanism that makes links with high flows less attractive.

Primarily dealing with determining the static link characteristics influencing bicycle route choice, a wide range of dedicated bicycle route choice models exist[6] – some of which also perform one-shot assignments of bicycle flows[7,8]. Other studies[9,10,11,12,13] have focused on assigning bicycles traffic onto networks including various link characteristics, but without any feedback from the network such as lowered safety or speeds influencing the route choice, although one of the studies[12] mentions it as a necessary extension. Another study[14] solely dealing with route choice also argues – as a suggestion for future research – that bicycle route choice models ought to incorporate congestion effects from traffic assignment models with dedicated bicycle volume-delay functions.

Nevertheless, until now the literature only contains one example[5] of such bicycle traffic assignment considering congestion effects. That study focuses on mixed traffic in Patna, India and assigns mixed traffic onto a multi-modal, shared network whilst taking the maximum speeds of trucks, cars, motorbikes, and bicycles into account. However, due to the chaotic Indian traffic scheme with mixed traffic being far from what is seen in a city with plenty of dedicated bicycle infrastructure, there still is a need for a dedicated bicycle traffic assignment model that can model congestion in segregated bicycle traffic.

The aim of this study is to fill this gap by assigning bicycle traffic onto a network at a large scale using an iterative feedback loop between the supply and the demand, as it is commonly known from motorised traffic. Based on a recently developed network loading model for heterogeneous bicycle traffic[15] this study includes detailed congestion patterns on link level, and forms a complete agent-based traffic assignment model for bicycles by allowing every cyclist to adjust his/her route according to the congested network.

The study does not deal with travel time delays caused by conflicting traffic at intersections nor traffic signals. We acknowledge that such delays cause substantial added travel time for cyclists. However, in order to keep focus on the large-scale applicability and consequences of the implemented network loading model such delays have been considered to be beyond the scope of this paper.

The remainder of the paper is structured as follows. Section 2 contains the applied methodology including a brief summary of the used network loading model[15]. The data used for the case study is described in Section 3, before presenting the results of said case study in Section 4. Finally, a discussion of the realism and the limitations of the model is found in Section 5 alongside suggestions for future research.

2. Methodology

In order to have an assignment model for bicycle traffic, it is necessary to be able to model how the demand influences the supply and vice versa. Plenty of route choice models for bicycle traffic exist[6], meaning that it is known to a large extend how the supply influences the demand for any link in the network. Until recently, however, it has been ignored how the supply is influenced by the demand predicted by such route choice models.

The network loading used in the assignment model of this study is a MATSim[16]-implementation of a recently proposed methodology[15] for dynamic, large-scale applicable network loading of bicycle traffic. The model is based on individual desired speeds for every cyclist corresponding to an individualised free-flow speed. It supports multi-lane links with each link having a predefined number of pseudo-lanes, allowing faster cyclists to overtake slower cyclists by placing themselves in the outermost lane(s) as long as there is room. If a cyclist can no longer choose a pseudo-lane that will satisfy his/her desired speed, the cyclist will choose the fastest available pseudo-lane. Furthermore, each cyclist has an individualised, speed dependent headway distance, that he/she must keep to the cyclist in front.

The speed of a cyclist entering a lane can be determined at link entrance solely based on his/her desired speed and headway preferences, as well as the time at which the previous entrant of the selected pseudo-lane is going to be leaving and entered the link, as neither overtaking nor lane changing are allowed within a lane. Because delays are based on the lack of opportunity to overtake, it also means that cyclists with high desired speeds have a higher tendency to be delayed, whereas it is virtually impossible for the overall slowest cyclist to be delayed. The methodology yields reasonable aggregate fundamental diagrams[15] as long as there is sufficient speed heterogeneity, and as such is best suited for agent-based transport modelling where individualised preferences can be assigned directly to each agent.

The route choice model used in this study is a simple multinomial logit model where the free flow travel time and congested travel time of alternatives are the only two variables used in the disutility function. The congested travel time, i.e. the difference between the actual travel time and the free flow travel time, is penalised 50 % harder than free flow travel time, in line with previous findings for car users in the area[17].

Each agent has a maximum number of five plans in his/her choice set, and after each iteration the performed plan is assigned a score based on the obtained travel time in the previous iteration. New plans are added to the choice set by performing a shortest path search in a network with empirical average travel times in time bins of 15 minutes based on the previous iteration. However, during the shortest path search the link cost of every link is agent-specific by using the maximum between the empirical (time binned) travel time and the free flow travel time based on that agent's desired speed.

Although the framework allows extension to include other link (to link) attributes previously seen in the literature such as signals, slope, surface, and left/right turns, for the time being only travel time is used in order to focus on the congestion caused by the network loading model.

The traffic assignment model has been implemented in the open-source and agent-based transport simulation software MATSim[16] by replacing parts of the default mobility simulator with the model from Paulsen et al. (2018)[15], alongside minor changes in the routing in order to account for individual desired speeds.

3. Case Study

In order to test the realism and the large-scale applicability of the model a case study for the greater Copenhagen area is carried out. The demand is based on the Copenhagen Model for Person Activity Scheduling (COMPAS)[18], producing daily activity plans for a synthetic population of the area. Only persons with a bicycle trip during his/her day have been used for this study, resulting in a population of 547,085 persons with daily activity plans forming a total of 1,082,958 bicycle trips.

Based on aerial data of observed, uncongested bicycle traffic on Smallegade in Frederiksberg, every individual is assigned a normally distributed headway distance parameter and a desired speed (v_0 in m/s) based on Johnson's S_U distribution[19] with the estimated parameters $\gamma = -2.75$, $\xi = 3.67$, $\delta = 4.07$, and $\lambda = 3.49$,[15]

$$v_0 \sim \frac{\delta}{\lambda\sqrt{2\pi}\sqrt{1+\left(\frac{v_0-\xi}{\lambda}\right)^2}}\, e^{-\frac{1}{2}\left(\gamma+\delta\sinh^{-1}\left(\frac{v_0-\xi}{\lambda}\right)\right)^2}, \tag{1}$$

inferring a mean speed and standard deviation of roughly 22 km/h and 4 km/h, respectively. This distribution has the highest likelihood and lowest Kolmogorov-Snirnov statistic among 11 candidate distributions with estimated parameters, and does not deviate significantly from the empirical distribution from Smallegade according to the Kolmogorov-Smirnov Goodness-of-Fit test (p-value above 0.6).[15]

The network is based on OpenStreetMap (OSM)[20] and is included in MATSim by altering the default OSM network reader[21]. All link types that generally allow bicycle traffic have been included in the model unless the road explicitly stated that bicycle traffic was not allowed. Furthermore, any road where bicycle traffic is explicitly mentioned as allowed or designated has also been included in the network.

The network loading model[15] only needs the lengths and widths of the bicycle infrastructure of links. Lengths are always available and can always be extracted directly from the OSM data. Widths also play a vital part for the methodology, but are rarely available. On the few links where widths (ω^l) were available, the number of lanes were determined based on the widths according to a Danish study[22], that found the number of efficient lanes (Ψ^l) of bicycle traffic to be determined by,

$$\Psi^l = 1 + \left\lfloor \frac{\omega^l - 0.4\,m}{1.25\,m} \right\rfloor. \tag{2}$$

Widths were manually added to crucial arterial roads of Copenhagen – especially the *cycle superhighways* – before extracting the data from OSM. This was done in order to secure these links being capable of handing large amount of bicycle traffic. Where widths were not available, the type of bicycle infrastructure determined the number of lanes. Explicit cycleways where motorised traffic is not allowed, as well as roads with bicycles riding in lanes or tracks were given two pseudo-lanes, since practically all of such infrastructure in Denmark would be wide enough to form two efficient lanes. Roads with no information about cycleways and footpaths where bicycle traffic is allowed were only given a single lane, as the presence of cars and pedestrians in such cases will limit the possibility to overtake.

Table 1. Average travel time and congested time according to five different scenarios.

Scenario	Avg. Travel Time Per Trip	Avg. Congested Travel Time Per Trip
Unlimited Capacity (Desired Speed)	16.43 min	0.00 min
Actual Infrastructure (it. 0)	16.73 min	0.29 min
Actual Infrastructure (it. 200)	16.67 min	0.12 min
Single-Lane Infrastructure (it. 0)	18.76 min	2.33 min
Single-Lane Infrastructure (it. 200)	17.70 min	0.81 min

4. Results

The assignment model was run for the population and network described in Section 3 for a total of 200 iterations with fixed choice sets after 160 iterations. The average computation time per iteration was 14.9 minutes on a single node of a high performance computer with two 2.8 GHz deca-core processors with 120 GB RAM.

Table 1 shows the average travel time and congested travel time for five different scenarios. It is seen that in the very first iteration, corresponding to no one adapting their routes according to the network performance, using the actual infrastructure a cyclist would on an average get his/her average trip travel time prolonged by approximately 18 seconds of congested travel corresponding to just under 2 % of the total travel time. Due to the possibility to choose alternative routes, this number is eventually reduced so that the average congested travel time is 7 seconds (roughly 1 %) while lowering the overall travel time by a similar amount.

This may be interpreted as bicycle congestion being a non-issue. On the other hand, it can also be seen as an indication of how well the profound bicycle infrastructure found in Copenhagen is relieving congestion. This is supported by the two final rows of Table 1, which are based on model runs where all links only have a single pseudo-lane, thus radically reducing the possibility to overtake. With such an infrastructural setup, using distance based shortest path for every cyclist results in a travel time that is prolonged by an average of 2.03 minutes per trip (12 %). In such a scenario large benefits can be made by adapting the route, and eventually the excess travel time can be reduced to 1.03 minutes (6.2 %) with 48 seconds of the travel time being congested time, more than six times as much than with the actual infrastructure. It is worth noting that these numbers are average values across an area larger than the entire Capital Region of Denmark which also covers a lot of smaller towns and rural areas where bicycle congestion is practically non-existing. This means that the congested travel time of trips in the central parts of Copenhagen will be considerably higher than the average values across the entire area presented in the table.

In order to investigate how the route choice is affected by congestion in the central part of Copenhagen, a difference map based on the morning peak hour from 7am to 8am between the actual congested network and a free-flow assignment is presented in in Figure 1. At first it might be hard to see any clear patterns in the map, but including some local knowledge lets the map be understood more easily. In the south-eastern part of the map it is seen that a substantial amount of cyclists are avoiding Knippelsbro. More than 100 cyclists per direction deviate onto the Inner Harbour bridge, and for the busy north-western direction the route across Langebro also becomes a reasonable alternative. This indeed seems plausible as Torvegade (the street linking to Knippelsbro from south-east) has a relatively moderate bicycle infrastructure that only allows two efficient lanes per direction, although having one of the highest daily bicycle counts. In the other end of the city centre, it is seen that Queen Louise's Bridge is gaining cyclists due to congestion from competing bridges. This seems intuitive as this bridge and Nørrebrogade (the street linking to Queen Louise's Bridge from north-west) forms a corridor that predominantly have three efficient lanes following a radical renovation in 2011, and is considered as the main arterial road for bicycle traffic connecting westbound suburbs.

5. Conclusions & Future Work

In this study a traffic assignment model for bicycle traffic was proposed using a detailed, demand sensitive network loading model[15]. A large-scale case study was conducted for the greater Copenhagen area with running times proving that the presented methodology is in fact large-scale applicable.

The results have shown that based on the proposed model, congestion related route changes does seem to happen in Copenhagen with some cyclists avoiding the most congested links in favour of links with particularly wide bicycle

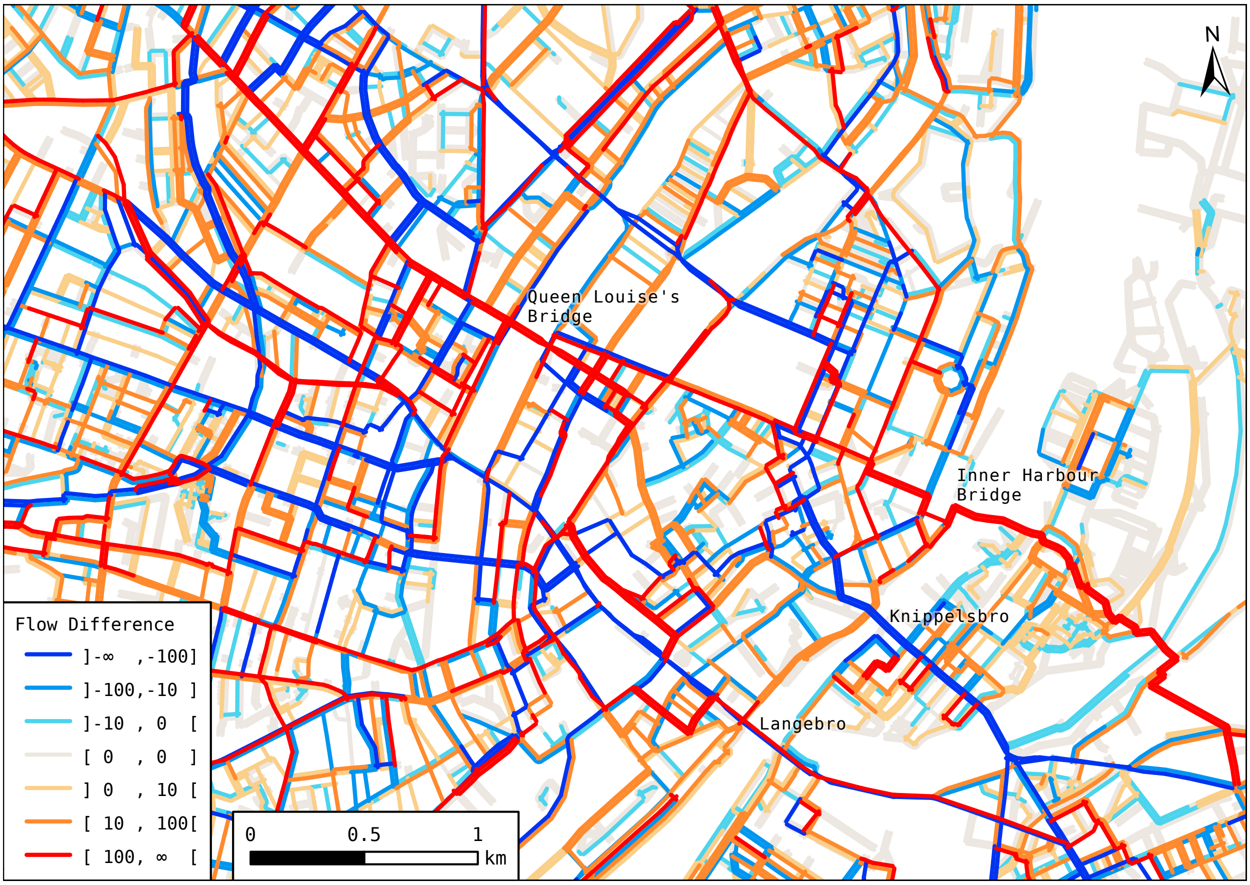

Fig. 1. Map with selected points of interests showing the difference in flow in the morning peak hour from 7 to 8 between modelled selected routes and routes found by using a free-flow, distance-based assignment.

tracks. The results also showed that having a comprehensive, decent bicycle infrastructure can greatly reduce the travel time of cyclists. However, this effect is likely overestimated with the current study as the single-lane scenario implies no opportunity to overtake altogether. In reality cyclists do tend to find a way of overtaking, why the predicted travel times will probably be pessimistic for the fastest cyclists.

Even though the travel time gains are possibly overestimated, the study only includes travel time as a parameter. In reality, better infrastructure is inherently attractive for cyclists [1], and will also improve the perceived safety of cyclists. Parameters that this study do not deal with explicitly, although it would be interesting to include in future research.

Furthermore, the methodology applied in this study only deals with delays on the links themselves. However, the majority of excess travel time for cyclists is possibly induced at intersections. In the morning peak hour certain core links in Copenhagen have bicycle queues that are often longer than what can be emptied in a single signal cycle. Delays can also happen when cyclists are waiting for through-going traffic when making a left turn.

Such delays can be included directly in the mobility simulation by concurrently simulating motor vehicles and modelling right of way and signals at intersections. This would also capture how cyclists delay the remainder of traffic, meaning that it would be very suitable for project appraisal purposes. Although relevant, implementing such methodology would be a serious extension and possibly be on the limit on what is computationally feasible.

A pragmatic alternative could possibly be to include the number of turns and signals as parameters in the route choice model [23] and/or to apply fixed travel time penalties for every signal, left turn, and right turn, respectively. The literature on bicycle route choice modelling also contains additional link-specific parameters such as land-use [14], surface [14], and slope [24], which straightforwardly can and should be added to the model in future work, although slope is not a huge issue in the greater Copenhagen area.

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